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Title: Safeguarding Reactors and Spent Nuclear Fuel

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Safeguarding Reactors and Spent Nuclear Fuel

Actinide Science and Technology Lecture Series

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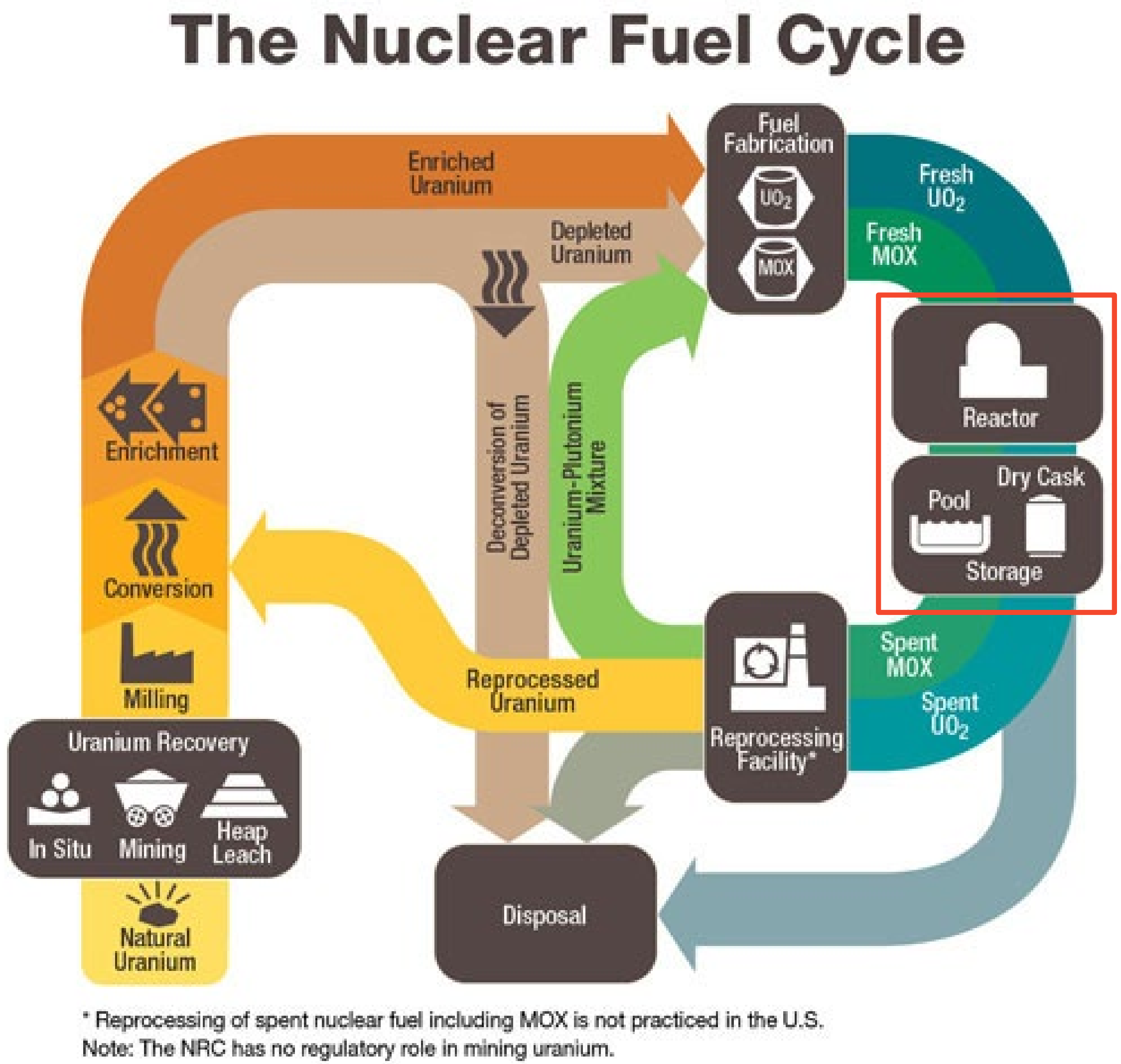
May 26, 2020

National Nuclear Security Administration
Managed by Triad National Security, LLC for the U.S. Department of Energy's NNSA

International Safeguards



NRC.gov

Reactors and Spent Fuel

Why is it relevant to safeguards?

- Highly enriched fuel contains large quantities of ^{235}U
- Burned fuel may contain large quantities of ^{239}Pu
  - Reprocessing is the major threat (discussed at length later), but we need to ensure the amount of plutonium going to the reprocessing plant is what we believe it to be
- All nuclear material needs to be accounted for (material accountancy)
  - There may be a loss of continuity of knowledge in which case fuel needs to be measured to determine how much plutonium and uranium it contains

Reactor Safeguards

Safeguards Approach

- Reactors are (more or less) self-safeguarding due to the high radiation levels during operation

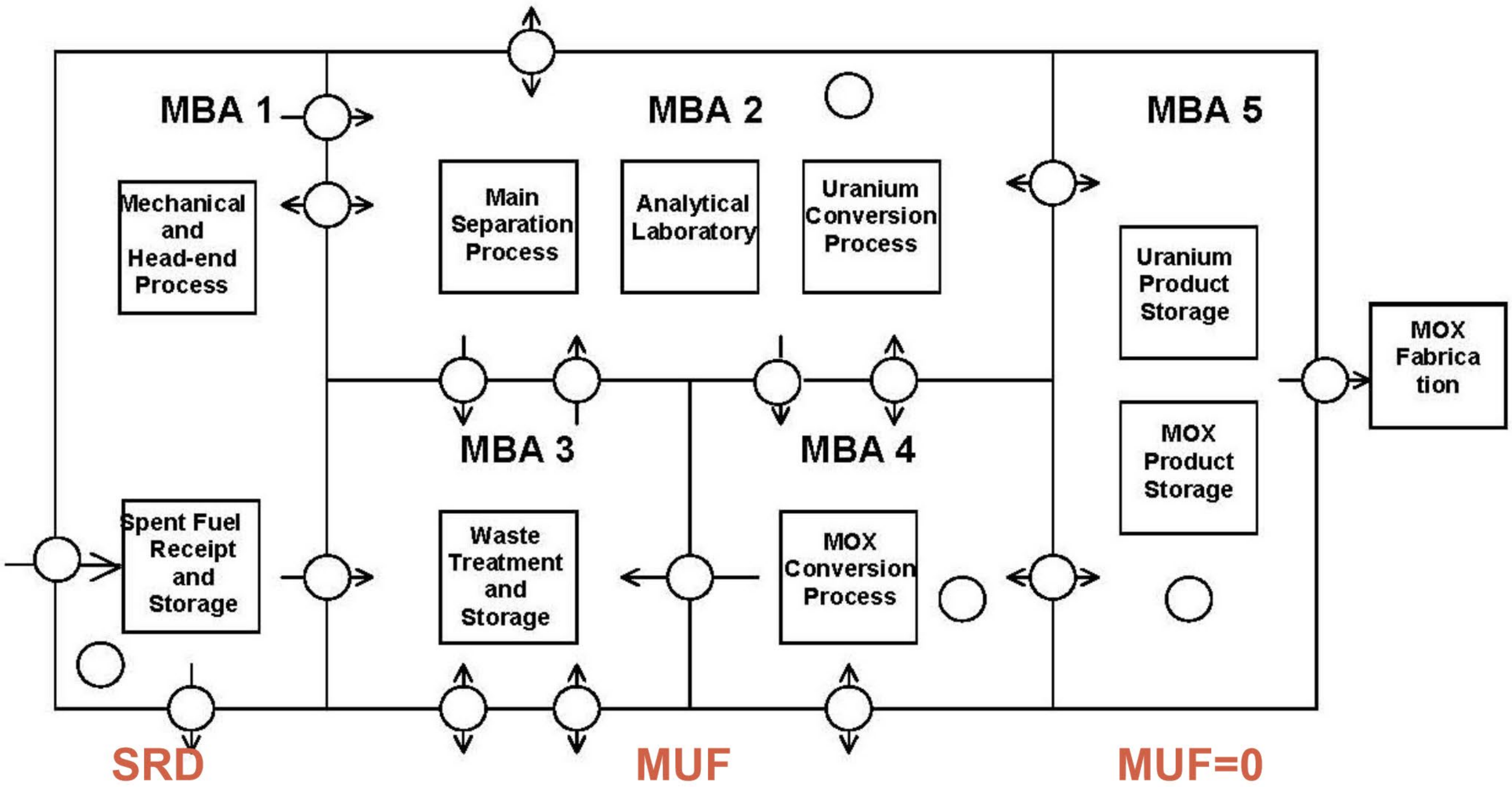
- Accountancy, containment, surveillance
  - Accountancy: Routine interim and physical inventory verification inspections, swipes of areas of interest (destructive analysis), nondestructive assay
  - Containment: Material balance areas
  - Surveillance: Remote monitoring, cameras, sensors

- IAEA inspectors implement this safeguards approach

Accountancy

- Item vs Bulk
  - Item form is where integrity of item remains unaltered
    - Reactors, critical assemblies, laboratories, etc.
    - Tags and seals
  - Bulk form is pellets, powders, liquids, gases and accountancy often organized into material balance area (MBA) form
    - Conversion, enrichment, fuel fabrication, reprocessing, etc.
- In item form, items can simply be counted
- In bulk form, material is in constant movement and may change location, physical form, even chemical composition
- Material quantities are recorded for different balance areas and transfers between balance areas must be recorded as well
  - Receipts and shipments
  - Accidental loss or gain
  - Measured discard
  - Termination of safeguards for non-nuclear use

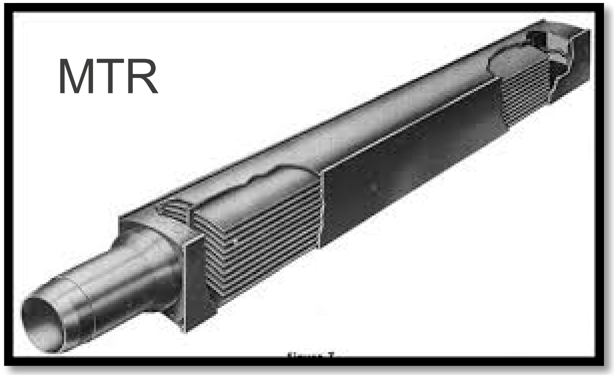
MBAs example

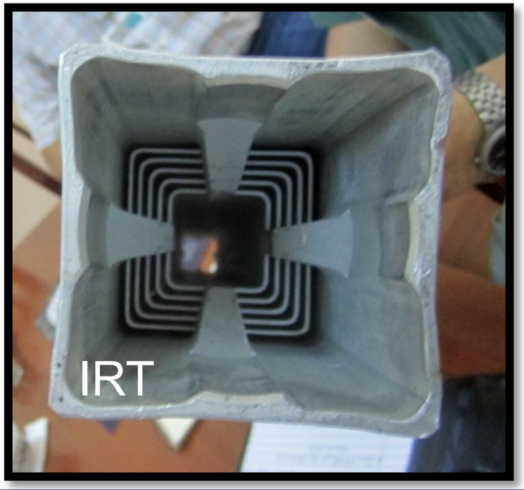


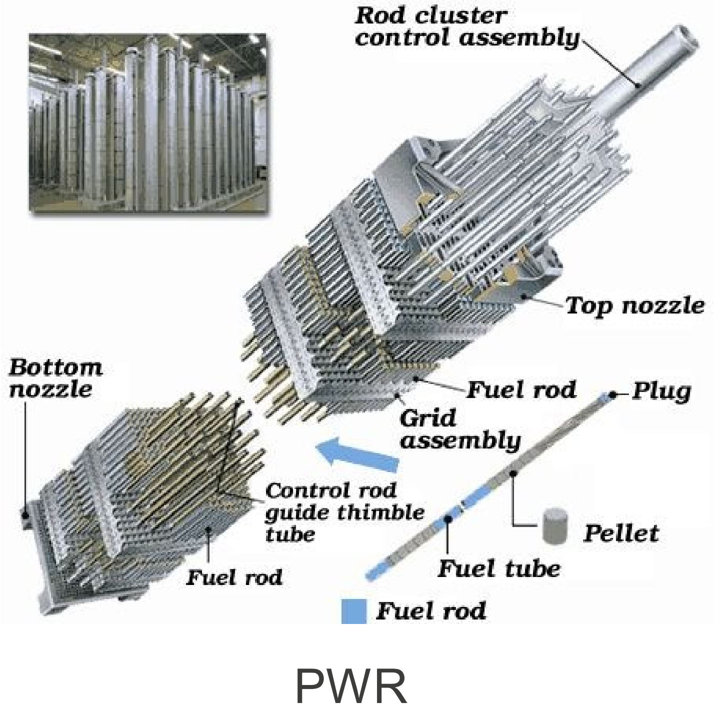
Spent Fuel NDA

Spent Fuel NDA: Objectives

- Verify operator declaration of residual uranium, and buildup of plutonium
  - Burnup
  - Initial enrichment
- Verify cooling time of assembly to assist with other parameters
- Verify completeness of assemblies

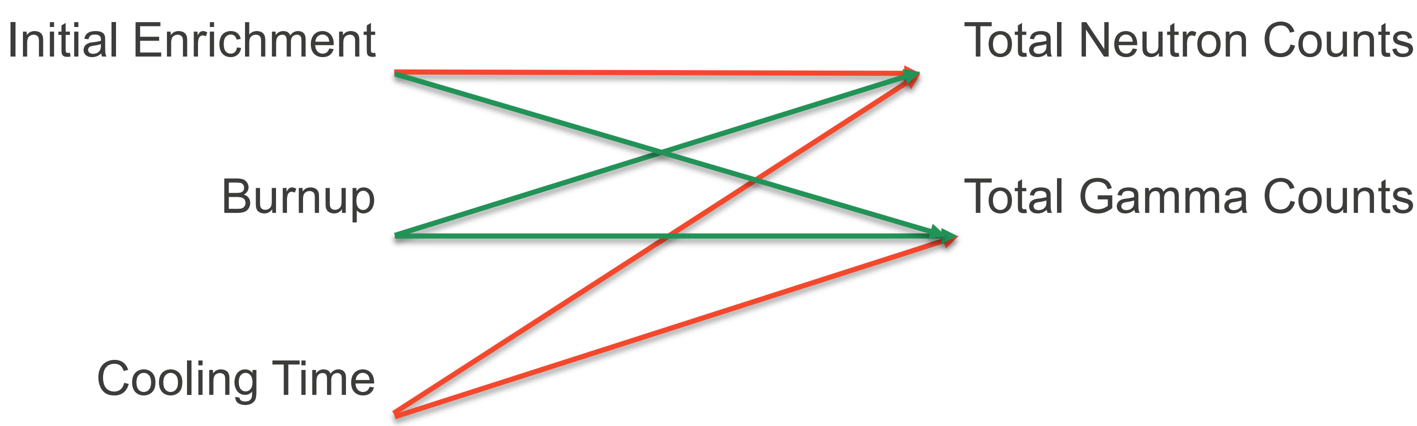






Spent Fuel NDA: Challenges

- Interruptions to reactor operations
  – Nuclear facilities have a standard way of operating and large disruptions (i.e. long measurements, drastic fuel movement) are not acceptable
- Fuel inhomogeneity
  – Both axially and radially, neutron flux in the reactor affects burnup, resulting in inhomogeneous fuel assemblies
- Competing parameters



- Very difficult to accurately model
  – Burnup codes are highly dependent on the accuracy of nuclear data and reactor operating history

Power Reactor vs. Research Reactor

- Why are these two ***wildly*** different characterization problems?

	Power	Research
Size	~4 m long, 20 cm across, 1000 lbs	~80 cm long, 8 cm across, 13 lbs
Neutrons	~1E8 1/s	~1E4 1/s
Neutron Emitters	^{242}Cm, ^{244}Cm, ^{240}Pu	^{240}Pu
Operating History	Predictable, $$$	Unpredictable, research
Easy Availability of Calibration Standards?	Nope!	Nope!

Currently Employed Techniques

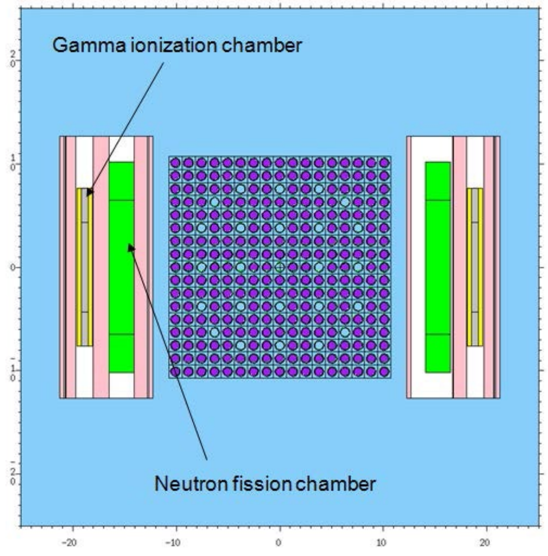
Fork Detector

- NDA technique widely used by the IAEA and EURATOM
- Detector system straddles light water reactor fuel assemblies with four fission chambers (neutrons) and two ion chambers (gammas)
  - Total gamma and neutron intensities as well as ratios of intensities give information about fuel assembly such as cooling time and burnup
  - One of the fission chambers is wrapped in cadmium to provide a means for estimating multiplication
- Other versions of the Fork detector exist with ^{3}He tubes instead of fission chambers, etc.

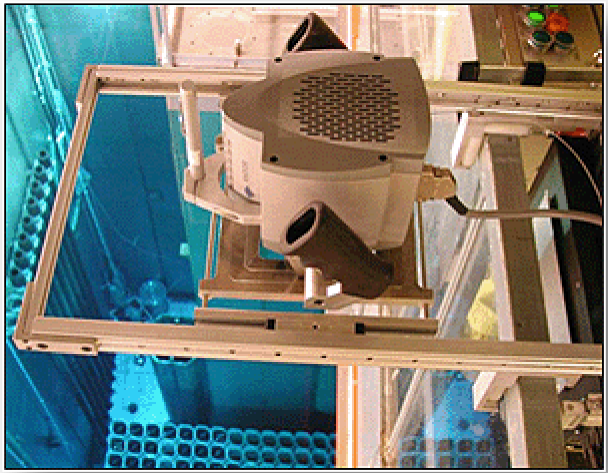
Fork Detector

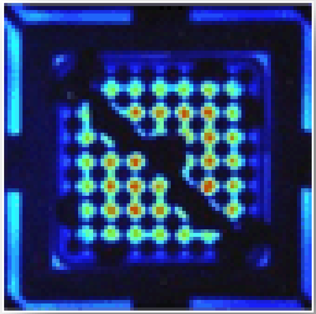
- Benefits
  - Rugged, reliable, validated and verified, easy to use
  - Requires minimal fuel movement

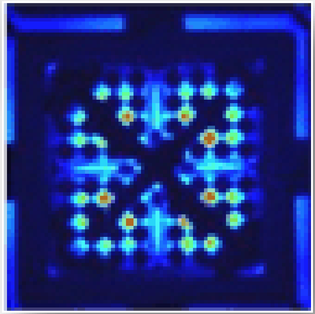
- Drawbacks
  - Asymmetric burnup could affect gamma signal
  - Assumptions about how neutron and gamma counts trend with burnup and cooling time fall apart under irregular burning history
  - Results rely heavily upon data provided by operator
  - May not be able to detect pin removal under 50%



Digital Cerenkov Viewing Device



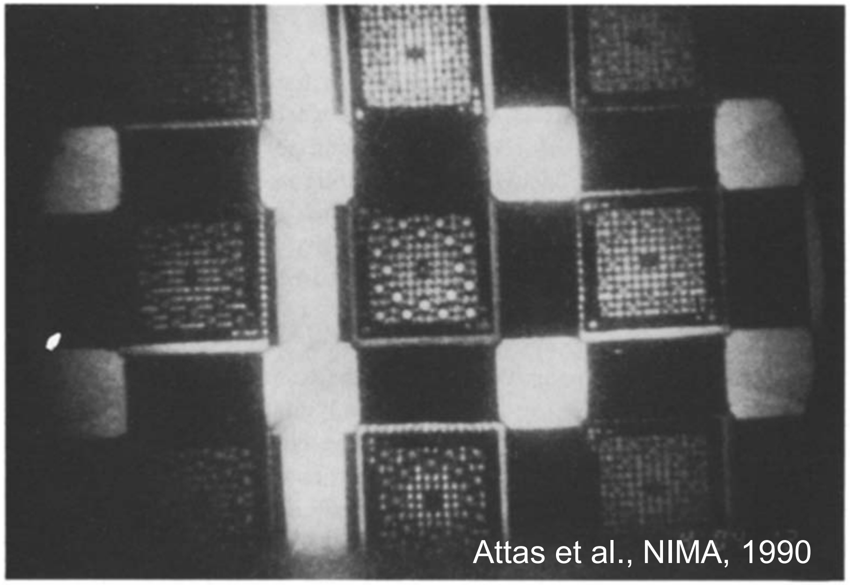




- Viewing device sensitive to ultraviolet radiation in the water surrounding spent fuel
- Cerenkov radiation provides the UV light and is derived from the intense gamma radiation in spent fuel
- Electrons may exceed the speed of light in water and therefore must lose energy by emitting Cerenkov radiation. β particles contribute as well
- Glow patterns above fuel rods used to distinguish fuel from non-fuel

Digital Cerenkov Viewing Device

- Benefits:
  - Tested, validated method with reliable history of use
  - Readily detects missing fuel rods
  - Burnup and cooling time verification
  - Indirect measurement method, meaning fuel assemblies may remain in storage positions

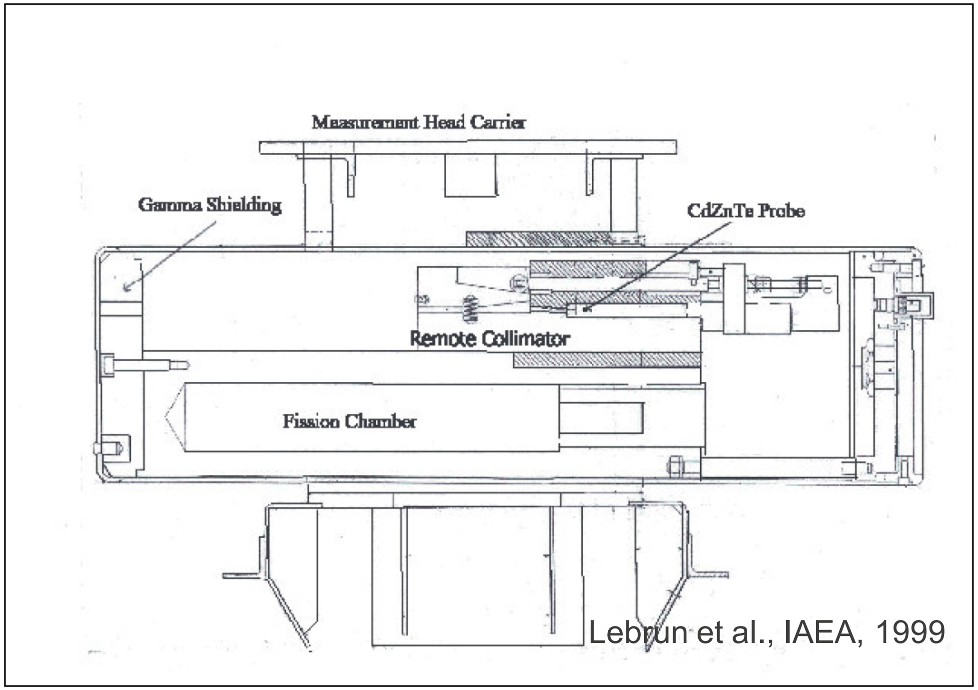


Attas et al., NIMA, 1990

- Drawbacks:
  - Murky water or weak Cerenkov signals can inhibit ability to use CVDs
  - Neighboring assemblies in pool can confuse measurement
  - Limited to certain burnups and cooling times due to required signal strength
  - Potentially easy to fool with cutoff pins or fake fuel rods

Safeguards MOX Python (SMOPY)

- Total neutron counting combined with gamma spectroscopy
  - There are known minimum neutron emission rates in MOX assemblies and maximum rates for UOX assemblies
  - $^{134}Cs/^{137}Cs$ ratio used as burnup indicator
- System performs single neutron calibration measurement on known item to be used in similar campaigns

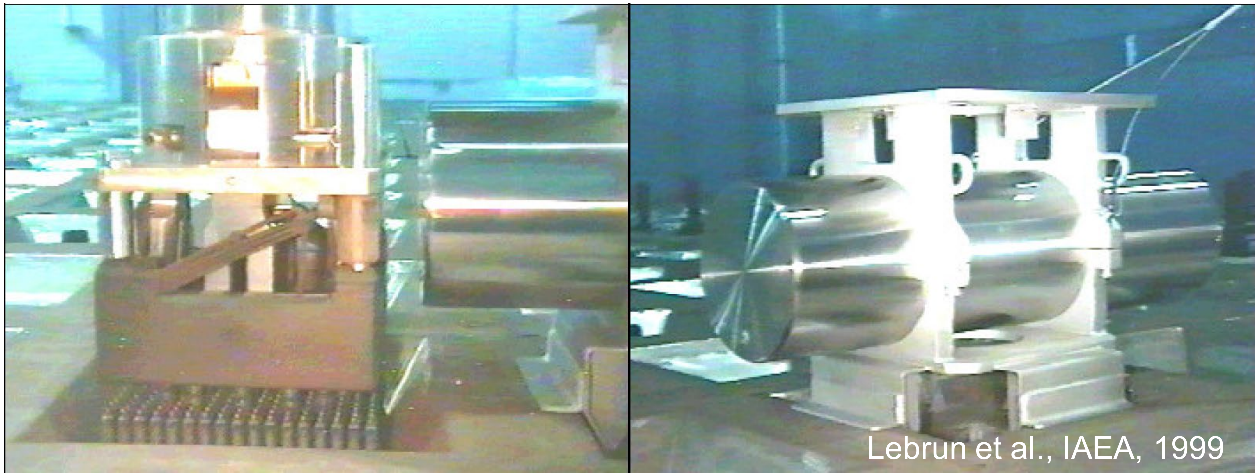


Lebrun et al., IAEA, 1999

Safeguards MOX Python (SMOPY)

- Benefits
  - Can be used on wide variety of assemblies, cooling from weeks to years, and burnups low to high
  - Simple technology and simple analysis
  - Relatively compact system

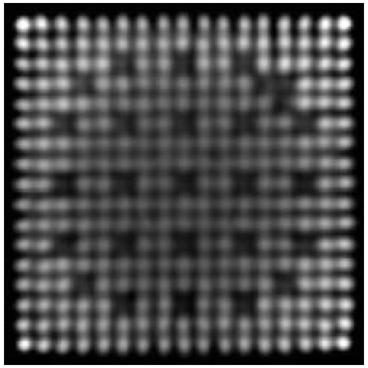
- Drawbacks
  - Self-shielding of gammas makes spectroscopy unreliable
  - Asymmetric assemblies or diversions present more issues for gamma use



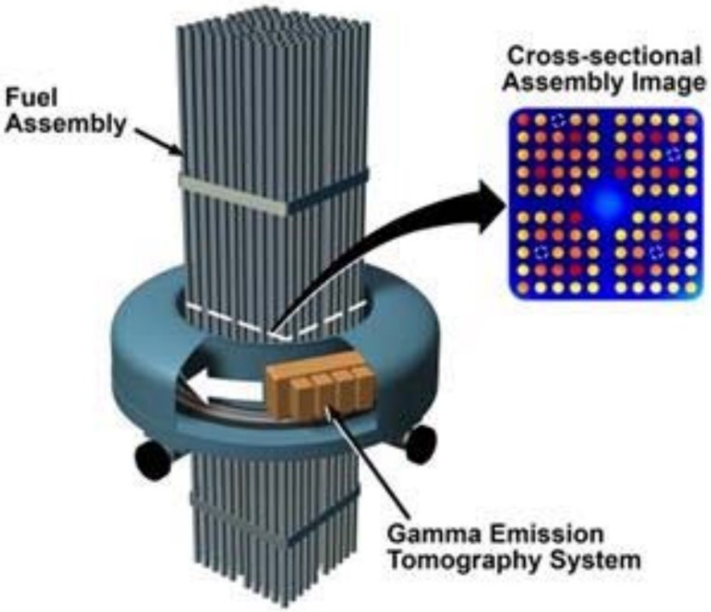
Lebrun et al., IAEA, 1999

Passive Gamma Emission Tomography (PGET)

- 2 ^{10}B and 174 collimated CZT detectors rotate around a power reactor fuel assembly to provide a tomographic image
- Measurements take 3-5 minutes
- Has been tested for burnups from 5.7-58 GWd/tU and cooling times from 1.9-27 years



Mayorov et al., IEEE, 2017



Miller et al., PNNL, 2017

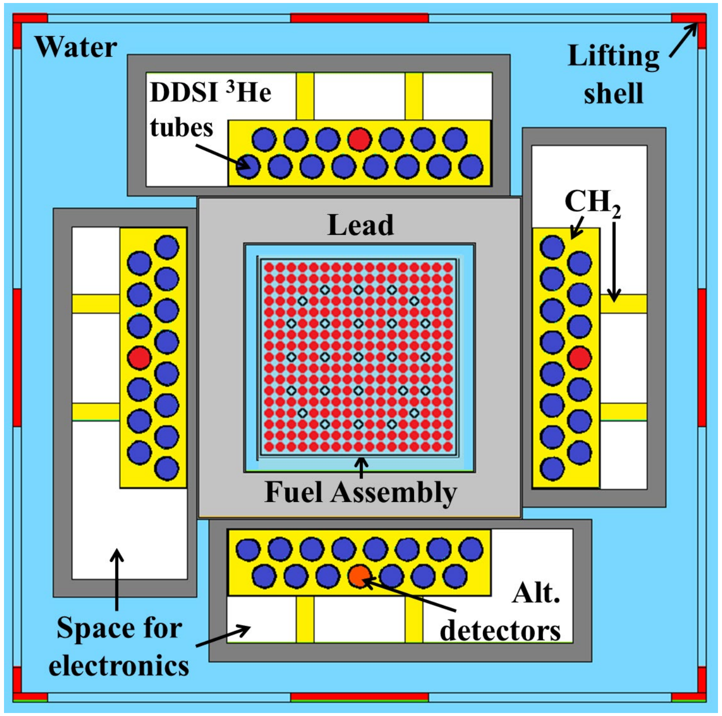
- **Missing pins are identified with image**
- **BU/CT declarations are verified with neutron and gamma spectroscopy information (Cs ratio)**

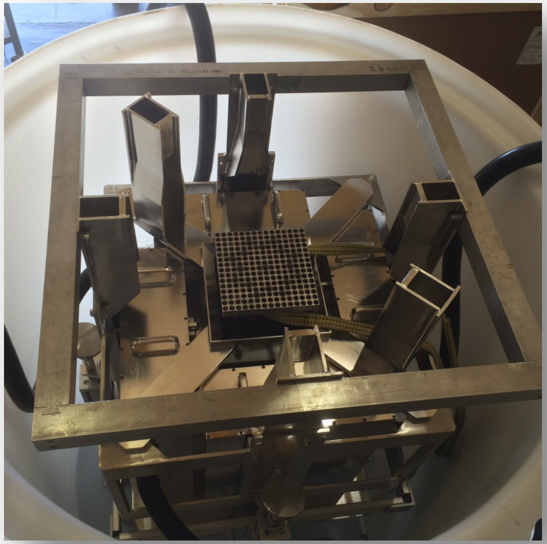
- **Benefits: Everything you need in one NDA system!**
- **Drawbacks: Intrusive**

Experimental Techniques

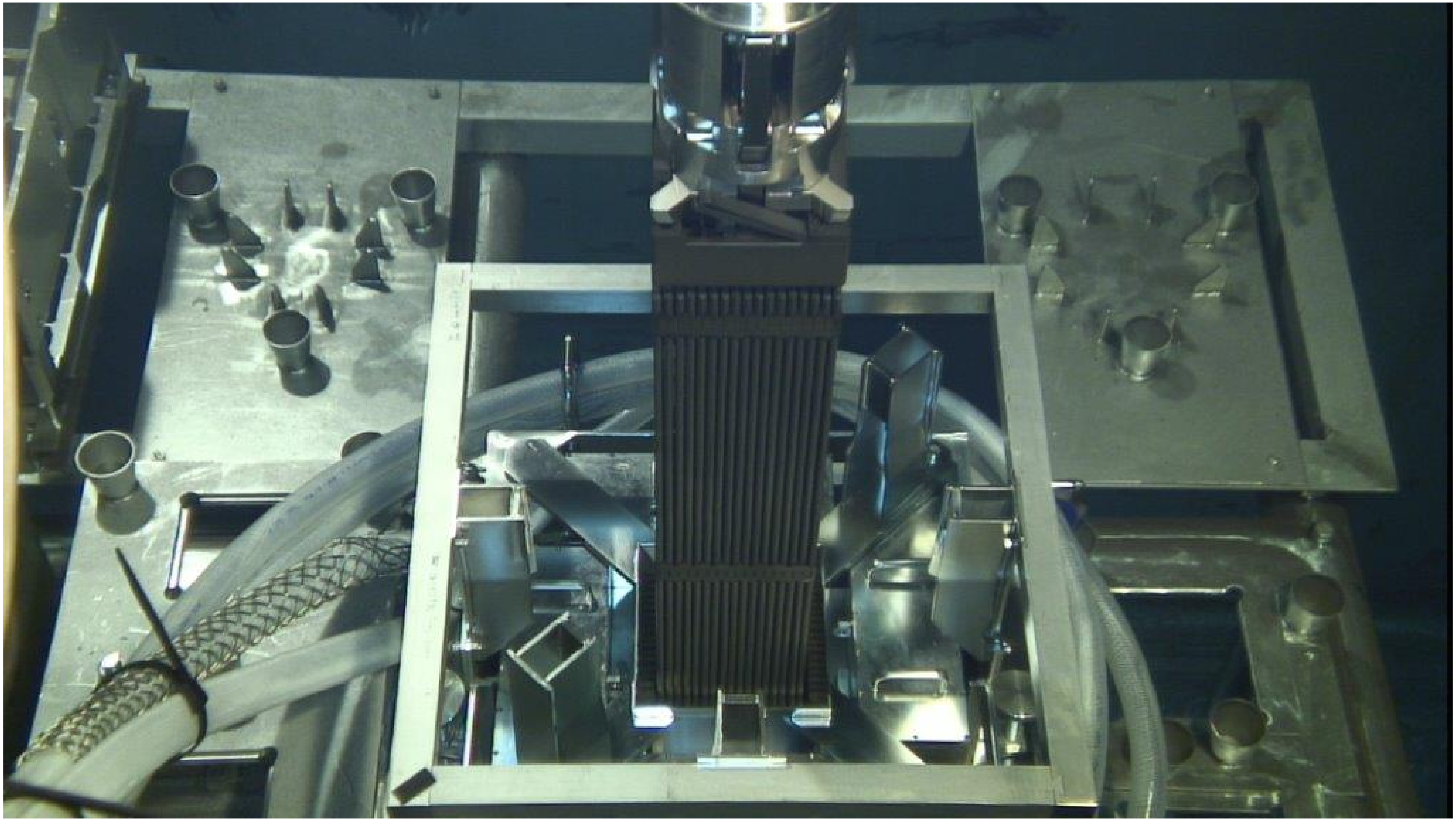
Differential Die-Away Self-Interrogation

- Spontaneous fission neutrons from ^{244}Cm, ^{240}Pu in spent fuel thermalize in water and interrogate fuel pins
- Neutron coincidence counting: aim to detect two neutrons that are temporally correlated
  – Same fission event, same fission chain
- Record times of neutron detections
  ➢ *list-mode data*



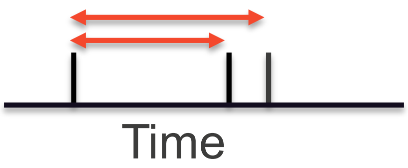


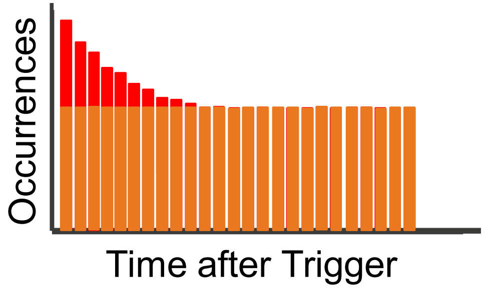
DDSI

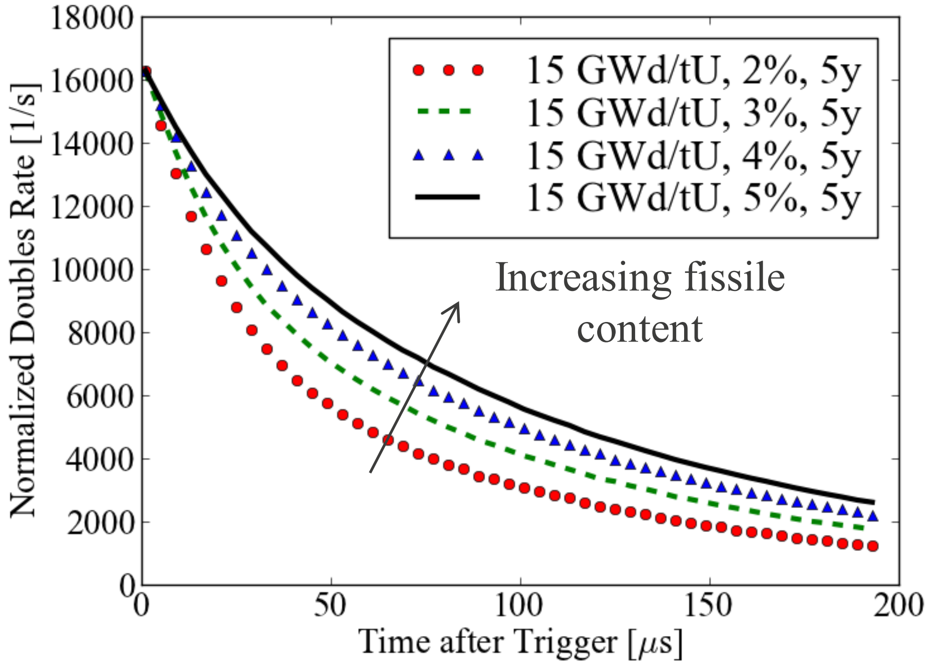


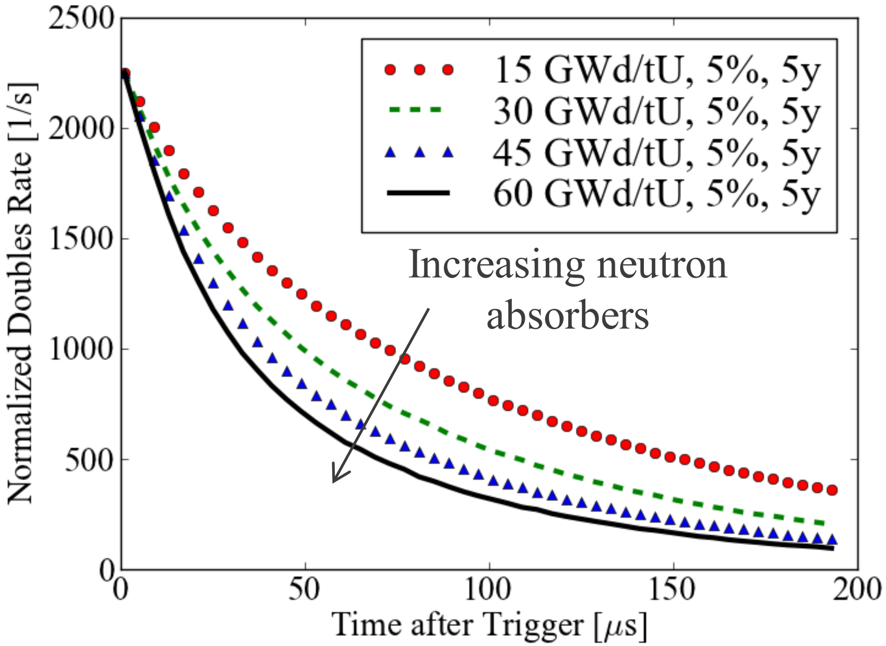
Differential Die-Away Self-Interrogation

- Rossi-alpha distribution is a histogram of the times between the trigger and each neutron in the gate



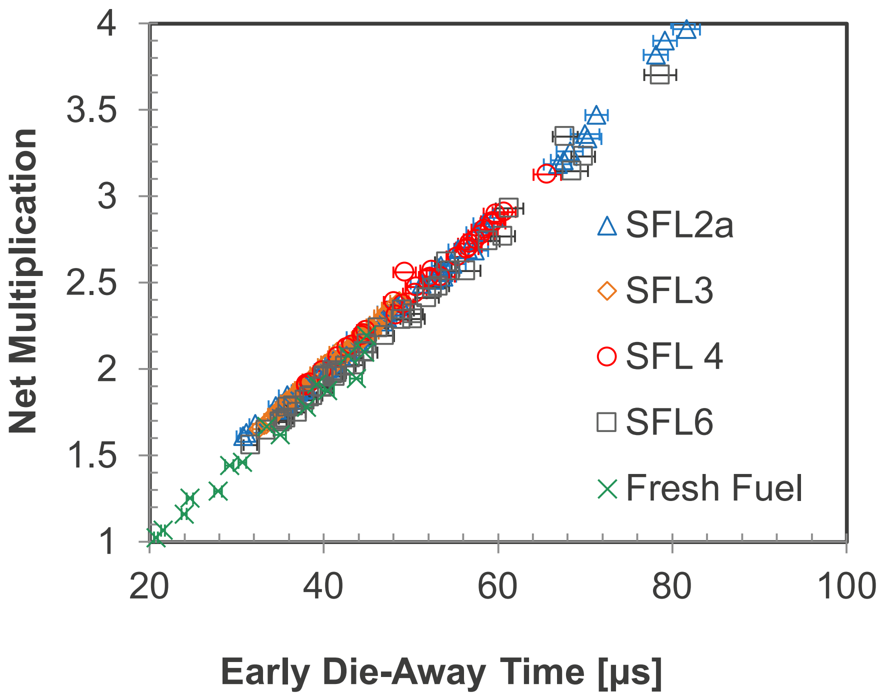




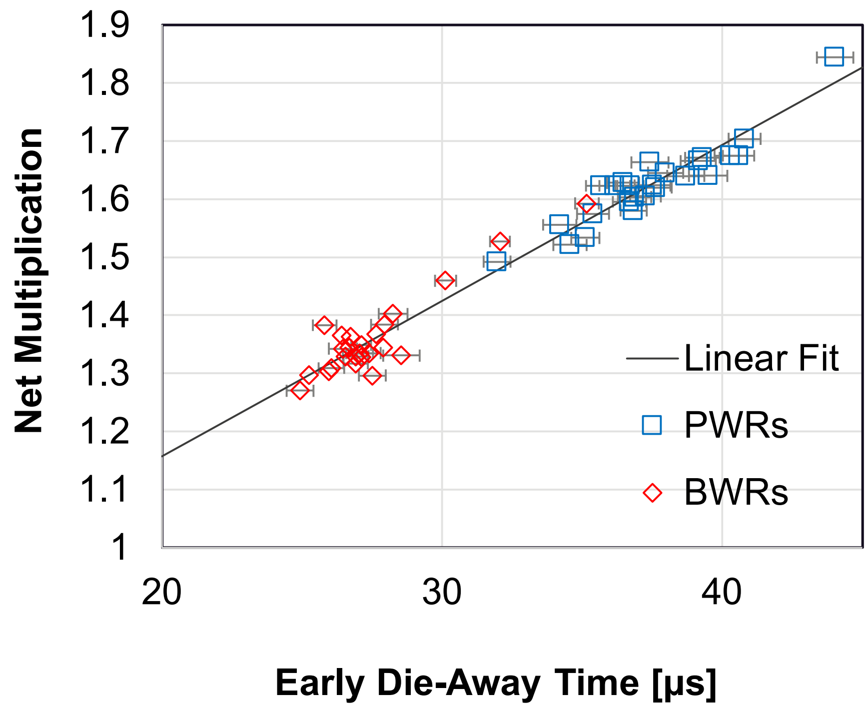


DDSI Analysis

- Early die-away time is nearly linearly proportional to assembly multiplication
  - Using this indicator, one can determine whether pins have been removed, or confirm BU, IE



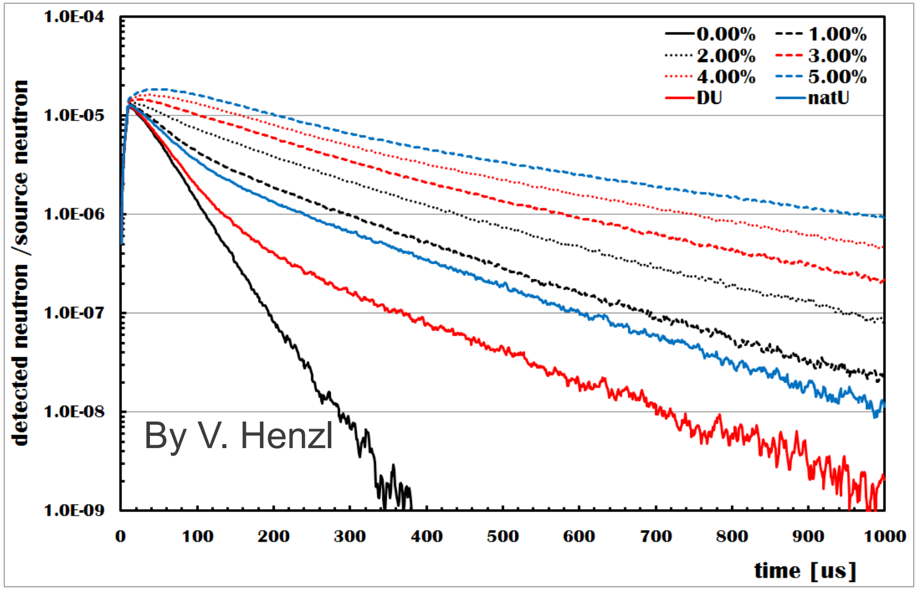
Simulation + Fresh Fuel measurements



Spent Fuel Experiments

Differential Die-Away

- “Sister Instrument” to DDSI– active version
- External neutron generator provides interrogating neutrons to induce fission
- Record neutron arrival times as a function of time after generator burst
- As fission chains die-away (because the system is subcritical) the induced fission signal dies-away as well

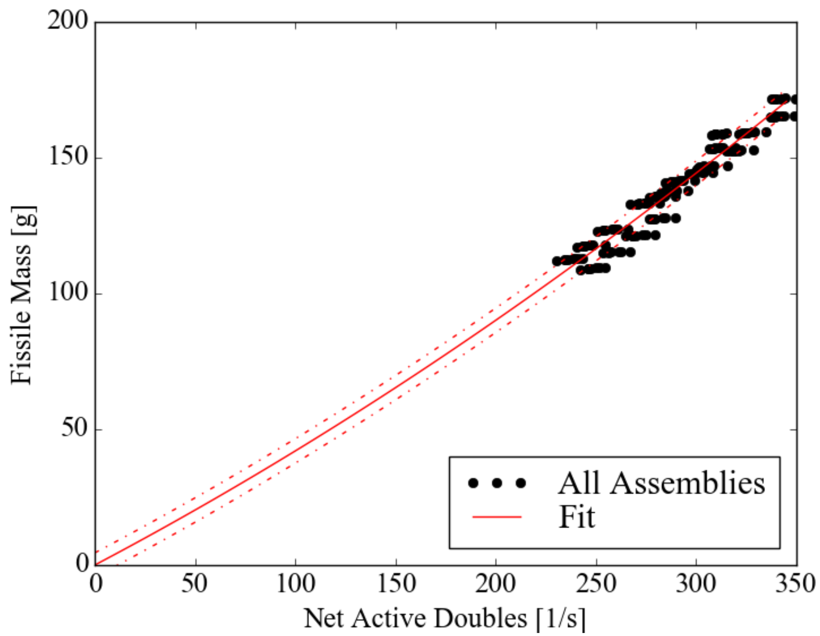


Advanced Experimental Fuel Counter

- Designed for research reactor fuel characterization
- System uses:
  - Active and passive neutron coincidence counting
  - An ion chamber for gross gamma-ray counting
- Measurement objective is to verify residual fissile mass (i.e., ^{235}U + ^{239}Pu) using neutron coincidence counting
- Field trials have occurred as follows:
  - 2006 High Flux Australian Reactor (HIFAR), Australia,
  - 2011 Institute of Nuclear Physics (INP), Uzbekistan
  - 2014 Institute of Nuclear Physics (INP), Uzbekistan
  - 2018 Soreq Nuclear Research Center, IRR-1, Israel

AEFC

- Simulated hundreds of spent fuel assemblies representing a wide range of depletion, cooling time, and operating history parameters
- "Measure" the simulated assemblies in the top, middle, and bottom positions in the AEFC
- Create calibration curve of fissile mass vs. net active doubles rate



- **Applying this generic calibration curve to fuel measured in a previous field trial, we were able to determine the residual fissile mass with a root mean square error of ~5%**

Thank you!